the surfaces surrounding the pressure ports shall be noted because of the potential effect on the probe's pressure readings. If the probe has been previously calibrated, compare the current condition of the probe's pressure ports and surfaces to the results of the inspection performed during the probe's most recent wind tunnel calibration. Record the results of this inspection on a form and in diagrams similar to Table 2F–1. The information in Table 2F–1 will be used as the basis for comparison during the probe head inspections performed before each subsequent field use.

10.3 Pre-Calibration Procedures. Prior to calibration, a scribe line shall have been placed on the probe in accordance with section 10.4. The yaw angle and velocity calibration procedures shall not begin until the pretest requirements in sections 10.3.1 through 10.3.4 have been met.

10.3.1 Perform the horizontal straightness check described in section 8.2 on the probe assembly that will be calibrated in the wind tunnel.

10.3.2 Perform a leak check in accordance with section 8.4.

10.3.3 Except as noted in section 10.3.3.3, calibrate all differential pressure-measuring devices to be used in the probe calibrations, using the following procedures. At a minimum, calibrate these devices on each day that probe calibrations are performed.

10.3.3.1 Procedure. Before each wind tunnel use, all differential pressure-measuring devices shall be calibrated against the reference device specified in section 6.4.3 using a common pressure source. Perform the calibration at three reference pressures representing 30, 60, and 90 percent of the full-scale range of the pressure-measuring device being calibrated. For an inclined-vertical manometer, perform separate calibrations on the inclined and vertical portions of the measurement scale, considering each portion of the scale to be a separate full-scale range. [For example, for a manometer with a 0- to 2.5-cm $H_2O$ (0- to 1-in. $H_2O$) inclined scale and a 2.5- to 12.7-cm $H_2O$ (1- to 5-in. $H_2O$) vertical scale, calibrate the inclined portion at 7.6, 15.2, and 22.9 mm $H_2O$ (0.3, 0.6, and 0.9 in. $H_2O$), and calibrate the vertical portion at 3.8, 7.6, and 11.4 cm $H_2O$ (1.5, 3.0, and 4.5 in. $H_2O$).] Alternatively, for the vertical portion of the scale, use three evenly spaced reference pressures, one of which is equal to or higher than the highest differential pressure expected in field applications.

10.3.3.2 Acceptance criteria. At each pressure setting, the two pressure readings made using the reference device and the pressure-measuring device being calibrated shall agree to within ±2 percent of full scale of the device being calibrated or 0.5 mm $H_2O$ (0.02 in. $H_2O$), whichever is less restrictive. For an inclined-vertical manometer, these requirements shall be met separately using the respective full-scale upper limits of the inclined and vertical portions of the scale. Differential pressure-measuring devices not meeting the #2 percent of full scale or 0.5 mm $H_2O$ (0.02 in. $H_2O$) calibration requirement shall not be used.

10.3.3.3 Exceptions. Any precision manometer that meets the specifications for a reference device in section 6.4.3 and that is not used for field testing does not require calibration, but must be leveled and zeroed before each wind tunnel use. Any pressure device used exclusively for yaw nulling does not require calibration, but shall be checked for responsiveness to rotation of the probe prior to each wind tunnel use.

10.3.4 Calibrate digital inclinometers on each day of wind tunnel or field testing (prior to beginning testing) using the following procedures. Calibrate the inclinometer according to the manufacturer's calibration procedures. In addition, use a triangular block (illustrated in Figure 2F–12) with a known angle, θ independently determined using a protractor or equivalent device, between two adjacent sides to verify the inclinometer readings.

NOTE: If other angle-measuring devices meeting the provisions of section 6.2.3 are used in place of a digital inclinometer, comparable calibration procedures shall be performed on such devices.)

Secure the triangular block in a fixed position. Place the inclinometer on one side of the block (side A) to measure the angle of inclination ($R_1$). Repeat this measurement on the adjacent side of the block (side B) using the inclinometer to obtain a second angle reading ($R_2$). The difference of the sum of the two readings from 180° (i.e., $180° - R_1 - R_2$) shall be within ±2° of the known angle, Θ

10.4 Placement of Reference Scribe Line. Prior to the first calibration of a probe, a line shall be permanently inscribed on the main probe sheath to serve as a reference mark for determining yaw angles. Annex C in section 18 of this method gives a guideline for placement of the reference scribe line.

10.4.1 This reference scribe line shall meet the specifications in sections 6.1.6.1 and 6.1.6.3 of this method. To verify that the alignment specification in section 6.1.6.3 is met, secure the probe in a horizontal position and measure the rotational angle of each scribe line and scribe line segment using an angle-measuring device that meets the specifications in section 6.2.1 or 6.2.3. For any scribe line that is longer than 30.5 cm (12 in.), check the line's rotational position at 30.5-cm (12-in.) intervals. For each line segment that is 30.5 cm (12 in.) or less in length, check the rotational position at the two endpoints of the segment. To meet the alignment specification in section 6.1.6.3, the minimum and maximum of all of the rotational angles that are measured along the full length of the main probe must not differ by more than 2°.

NOTE: A short reference scribe line segment [e.g., 15.2 cm (6 in.) or less in length] meeting the alignment specifications in section 6.1.6.3 is fully acceptable under this method. See section 18.1.1.1 of Annex A for an example of a probe marking procedure, suitable for use with a short reference scribe line.

10.4.2 The scribe line should be placed on the probe first and then its offset from the yaw-null position established (as specified in section 10.5). The rotational position of the reference scribe line relative to the yaw-null position of the probe, as determined by the yaw angle calibration procedure in section 10.5, is defined as the reference scribe line rotational offset, $R_{SLO}$. The reference scribe line rotational offset shall be recorded and retained as part of the probe's calibration record.

10.4.3 Scribe line for automated probes. A scribe line may not be necessary for an automated probe system if a reference rotational position of the probe is built into the probe system design. For such systems, a ''flat'' (or comparable, clearly identifiable physical characteristic) should be provided on the probe casing or flange plate to ensure that the reference position of the probe assembly remains in a vertical or horizontal position. The rotational offset of the flat (or comparable, clearly identifiable physical characteristic) needed to orient the reference position of the probe assembly shall be recorded and maintained as part of the automated probe system's specifications.

10.5 Yaw Angle Calibration Procedure. For each probe used to measure yaw angles with this method, a calibration procedure shall be performed in a wind tunnel meeting the specifications in section 10.1 to determine the rotational position of the reference scribe line relative to the probe's yaw-null position. This procedure shall be performed on the main probe with all devices that will be attached to the main probe in the field [such as thermocouples or resistance temperature detectors (RTDs)] that may affect the flow around the probe head. Probe shaft extensions that do not affect flow around the probe head need not be attached during calibration. At a minimum, this procedure shall include the following steps.

10.5.1 Align and lock the angle-measuring device on the reference scribe line. If a marking procedure (such as that described in section 18.1.1.1) is used, align the angle-measuring device on a mark within ±1° of the rotational position of the reference scribe line. Lock the angle-measuring device onto the probe sheath at this position.

10.5.2 Zero the pressure-measuring device used for yaw nulling.

10.5.3 Insert the probe assembly into the wind tunnel through the entry port, positioning the probe's impact port at the calibration location. Check the responsiveness of the pressure-measurement device to probe rotation, taking corrective action if the response is unacceptable.

10.5.4 Ensure that the probe is in a horizontal position, using a carpenter's level.

10.5.5 Rotate the probe either clockwise or counterclockwise until a yaw null ($P_2 = P_3$) is obtained.

10.5.6 Use the reading displayed by the angle-measuring device at the yaw-null position to determine the magnitude of the reference scribe line rotational offset, $R_{SLO}$, as defined in section 3.15. Annex D in section 18 of this method provides a recommended procedure for determining the magnitude of $R_{SLO}$ with a digital inclinometer and a second procedure for determining the magnitude of $R_{SLO}$ with a protractor wheel and pointer device. Table 2F–6 presents an example data form and Table 2F–7 is a look-up table with the recommended procedure. Procedures other than those recommended in Annex D in section 18 may be used, if they can determine $R_{SLO}$ to within ±1° and are explained in detail in the field test report. The algebraic sign of $R_{SLO}$ will either be positive, if the rotational position of the reference scribe line (as viewed from the ''tail'' end of the probe) is clockwise, or negative, if counterclockwise with respect to the probe's yaw-null position. (This is illustrated in Figure 2F–13.)

10.5.7 The steps in sections 10.5.3 through 10.5.6 shall be performed twice at each of the velocities at which the probe will be calibrated (in accordance with section 10.6). Record the values of $R_{SLO}$.

10.5.8 The average of all of the $R_{SLO}$ values shall be documented as the reference scribe line rotational offset for the probe.

10.5.9 Use of reference scribe line offset. The reference scribe line rotational offset shall be used to determine the yaw angle of flow in accordance with section 8.9.4.

10.6 Pitch Angle and Velocity Pressure Calibrations. Use the procedures in sections 10.6.1 through 10.6.16 to generate an appropriate set (or sets) of pitch angle and velocity pressure calibration curves for each probe. The calibration procedure shall be performed on the main probe and all devices that will be attached to the main probe in the field (e.g., thermocouple or RTDs) that may affect the flow around the probe head. Probe shaft extensions that do not affect flow around the probe head need not be attached during calibration. (Note: If a sampling nozzle is part of the assembly, a wind tunnel demonstration shall be performed that shows the probe's ability to measure velocity and yaw null is not impaired when the nozzle is drawing a sample.) The calibration procedure involves generating two calibration curves, $F_1$ versus pitch angle and $F_2$ versus pitch angle. To generate these two curves, $F_1$ and $F_2$ shall be derived using Equations 2F–1 and 2F–2, below. Table 2F–8 provides an example wind tunnel calibration data sheet, used to log the measurements needed to derive these two calibration curves.

10.6.1 Calibration velocities. The tester may calibrate the probe at two nominal wind tunnel velocity settings of 18.3 m/sec and 27.4 m/sec (60 ft/sec and 90 ft/sec) and average the results of these calibrations, as described in section 10.6.16.1, in order to generate a set of calibration curves. If this option is selected, this single set of calibration curves may be used for all field applications over the entire velocity range allowed by the method. Alternatively, the tester may customize the probe calibration for a particular field test application (or for a series of applications), based on the expected average velocity(ies) at the test site(s). If this option is selected, generate each set of calibration curves by calibrating the probe at two nominal wind tunnel velocity settings, at least one of which is greater than or equal to the expected average velocity(ies) for the field application(s), and average the results as described in section 10.6.16.1. Whichever calibration option is selected, the probe calibration coefficients ($F_2$ values) obtained at the two nominal calibration velocities shall, for the same pitch angle setting, meet the conditions specified in section 10.6.16.

10.6.2 Pitch angle calibration curve ($F_1$ versus pitch angle). The pitch angle calibration involves generating a calibration curve of calculated $F_1$ values versus tested pitch angles, where $F_1$ is the ratio of the pitch pressure to the velocity pressure, i.e.,

$$F_1 = \frac{\left(P_4 - P_5\right)}{\left(P_1 - P_2\right)} \qquad \text{Eq. 2F-1}$$

See Figure 2F–14 for an example $F_1$ versus pitch angle calibration curve.

10.6.3 Velocity calibration curve ($F_2$ versus pitch angle). The velocity calibration involves generating a calibration curve of the 3–D probe's $F_2$ coefficient against the tested pitch angles, where

$$F_2 = C_p \sqrt{\frac{\Delta P_{std}}{\left(P_1 - P_2\right)}} \qquad \text{Eq. 2F-2}$$

and

$C_p$ = calibration pitot tube coefficient, and

$\Delta P_{std}$ = velocity pressure from the calibration pitot tube.

See Figure 2F–15 for an example $F_2$ versus pitch angle calibration curve.

10.6.4 Connect the tested probe and calibration pitot probe to their respective pressure-measuring devices. Zero the pressure-measuring devices. Inspect and leak-check all pitot lines; repair or replace, if necessary. Turn on the fan, and allow the wind tunnel air flow to stabilize at the first of the two selected nominal velocity settings.

10.6.5 Position the calibration pitot tube at its measurement location (determined as outlined in section 6.11.4.3), and align the tube so that its tip is pointed directly into the flow. Ensure that the entry port surrounding the tube is properly sealed. The calibration pitot tube may either remain in the wind tunnel throughout the calibration, or be removed from the wind tunnel while measurements are taken with the probe being calibrated.

10.6.6 Set up the pitch protractor plate on the tested probe's entry port to establish the pitch angle positions of the probe to within ±2°.

10.6.7 Check the zero setting of each pressure-measuring device.

10.6.8 Insert the tested probe into the wind tunnel and align it so that its $P_1$ pressure port is pointed directly into the flow and is positioned within the calibration location (as defined in section 3.20). Secure the probe at the 0° pitch angle position. Ensure that the entry port surrounding the probe is properly sealed.

10.6.9 Read the differential pressure from the calibration pitot tube ($\Delta P_{std}$), and record its value. Read the barometric pressure to within ±2.5 mm Hg (±0.1 in. Hg) and the temperature in the wind tunnel to within 0.6°C (1°F). Record these values on a data form similar to Table 2F–8.

10.6.10 After the tested probe's differential pressure gauges have had sufficient time to stabilize, yaw null the probe, then obtain differential pressure readings for ($P_1$–$P_2$) and ($P_4$–$P_5$). Record the yaw angle and differential pressure readings. After taking these readings, ensure that the tested probe has remained at the yaw-null position.

10.6.11 Either take paired differential pressure measurements with both the calibration pitot tube and tested probe (according to sections 10.6.9 and 10.6.10) or take readings only with the tested probe (according to section 10.6.10) in 5° increments over the pitch-angle range for which the probe is to be calibrated. The calibration pitch-angle range shall be symmetric around 0° and shall exceed the largest pitch angle expected in the field by 5°. At a minimum, probes shall be calibrated over the range of −15° to +15°. If paired calibration pitot tube and tested probe measurements are not taken at each pitch angle setting, the differential pressure from the calibration pitot tube shall be read, at a minimum, before taking the tested probe's differential pressure reading at the first pitch angle setting and after taking the tested probe's differential pressure readings at the last pitch angle setting in each replicate.

10.6.12 Perform a second replicate of the procedures in sections 10.6.5 through 10.6.11 at the same nominal velocity setting.

10.6.13 For each replicate, calculate the $F_1$ and $F_2$ values at each pitch angle. At each pitch angle, calculate the percent difference between the two $F_2$ values using Equation 2F–3.

$$\%Diff = \frac{F_2^{max} - F_2^{min}}{F_2^{min}} \times 100\% \qquad \text{Eq. 2F-3}$$

If the percent difference is less than or equal to 2 percent, calculate an average $F_1$ value and an average $F_2$ value at that pitch angle. If the percent difference is greater than 2 percent and less than or equal to 5 percent, perform a third repetition at that angle and calculate an average $F_1$ value and an average $F_2$ value using all three repetitions. If the percent difference is greater than 5 percent, perform four additional repetitions at that angle and calculate an average $F_1$ value and an average $F_2$ value using all six repetitions. When additional repetitions are required at any pitch angle, move the probe by at least 5° and then return to the specified pitch angle before taking the next measurement. Record the average values on a form similar to Table 2F–9.

10.6.14 Repeat the calibration procedures in sections 10.6.5 through 10.6.13 at the second selected nominal wind tunnel velocity setting.

10.6.15 Velocity drift check. The following check shall be performed, except when paired calibration pitot tube and tested probe pressure measurements are taken at each pitch angle setting. At each velocity setting, calculate the percent difference between consecutive differential pressure measurements made with the calibration pitot tube. If a measurement differs from the previous measurement by more than 2 percent or 0.25 mm $H_2O$ (0.01 in. $H_2O$), whichever is less restrictive, the calibration data collected between these calibration pitot tube measurements may not be used, and the measurements shall be repeated.

10.6.16 Compare the averaged $F_2$ coefficients obtained from the calibrations at the two selected nominal velocities, as follows. At each pitch angle setting, use Equation 2F–3 to calculate the difference between the corresponding average $F_2$ values at the two calibration velocities. At each pitch angle in the −15° to +15° range, the percent difference between the average $F_2$ values shall not exceed 3.0 percent. For pitch angles outside this range (i.e., less than −15°0 and greater than +15°), the percent difference shall not exceed 5.0 percent.

10.6.16.1 If the applicable specification in section 10.6.16 is met at each pitch angle setting, average the results obtained at the two nominal calibration velocities to produce a calibration record of $F_1$ and $F_2$ at each pitch angle tested. Record these values on a form similar to Table 2F–9. From these values, generate one calibration curve representing $F_1$ versus pitch angle and a second curve representing $F_2$ versus pitch angle. Computer spreadsheet programs may be used to graph the calibration data and to develop polynomial equations that can be used to calculate pitch angles and axial velocities.

10.6.16.2 If the applicable specification in section 10.6.16 is exceeded at any pitch angle setting, the probe shall not be used unless: (1) the calibration is repeated at that pitch angle and acceptable results are obtained or (2) values of $F_1$ and $F_2$ are obtained at two nominal velocities for which the specifications in section 10.6.16 are met across the entire pitch angle range.

10.7 Recalibration. Recalibrate the probe using the procedures in section 10 either within 12 months of its first field use after its most recent calibration or after 10 field tests (as defined in section 3.4), whichever occurs later. In addition, whenever there is visible damage to the 3-D head, the probe shall be recalibrated before it is used again.

10.8 Calibration of pressure-measuring devices used in field tests. Before its initial use in a field test, calibrate each pressure-measuring device (except those used exclusively for yaw nulling) using the three-point calibration procedure described in section 10.3.3. The device shall be recalibrated according to the procedure in section 10.3.3 no later than 90 days after its first field use following its most recent calibration. At the discretion of the tester, more frequent calibrations (e.g., after a field test) may be performed. No adjustments, other than adjustments to the zero setting, shall be made to the device between calibrations.

10.8.1 Post-test calibration check. A single-point calibration check shall be performed on each pressure-measuring device after completion of each field test. At the discretion of the tester, more frequent single-point calibration checks (e.g., after one or more field test runs) may be performed. It is recommended that the post-test check be performed before leaving the field test site. The check shall be performed at a pressure between 50 and 90 percent of full scale by taking a common pressure reading with the tested device and a reference pressure-measuring device (as described in section 6.4.4) or by challenging the tested device with a reference pressure source (as described in section 6.4.4) or by performing an equivalent check using a reference device approved by the Administrator.

10.8.2 Acceptance criterion. At the selected pressure setting, the pressure readings